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RESEARCH MEMORANDUM

PERFORMANCE OF 24-INCH SUPERSONIC AXIAL-FLOW COMPRESSOR IN AIR

III - COMPRESSOR PERFORMANCE WITH INLET GUIDE VANES

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

As a continuation of the research program on supersonic axial-flow compressors, the 24-inch-diameter rotor was run with a set of inlet guide vanes designed to improve the relative inlet Mach number distribution near the hub. The inlet guide vanes were constructed of sheet-metal plates formed to airfoil mean-line shapes with design turning of about 7° in a counter-wheel-rotation direction. The results obtained with this set of inlet guide vanes are compared with the data obtained without inlet guide vanes.

The use of these inlet guide vanes resulted in a decrease in maximum pressure ratio and adiabatic efficiency and a slight increase in equivalent mass flow over most of the speed range of this investigation. The loss in total-pressure ratio and efficiency resulted from reduced diffusion in the rotor-blade passages and increased shock losses encountered at the higher entrance Mach number, as well as increased mixing losses accompanying increased boundary-layer thickness, separation, and transfer of mass flow toward the compressor hub. The unsteady flow field created at the compressor entrance by the wakes is also responsible for some of the losses in performance encountered in the use of inlet guide vanes. This inherent loss will be encountered whenever inlet guide vanes are used with the shock-in-rotor type supersonic compressor.

INTRODUCTION

It has been demonstrated (references 1 and 2) that the shock-in-rotor type supersonic compressor can produce a high stage pressure ratio and a high mass flow per unit annular area. In the first investigation conducted on this compressor rotor, very few mechanical difficulties, such as blade vibration or leading-edge damage, were encountered. It therefore appears that a compressor of the shock-in-rotor type may fulfill some of the requirements of the turbojet engine.

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The material presented in this report is a continuation of the compressor investigation reported in references 1 and 2. In references 1 and 2, true design operation was not obtained at the design equivalent tip speed of 1600 feet per second because the Mach number relative to the rotor blades at the hub section was not high enough for shock attachment to the 10° leading-edge wedge angle. In the previous investigation, the relative entrance Mach number was increased by overspeeding the compressor, which produced performance characteristics similar to those expected for this supersonic compressor. It was thought, however, that improved performance could be obtained at an equivalent tip speed of 1600 feet per second if a slightly higher relative entrance Mach number was obtained at the compressor hub through the use of inlet guide vanes.

A set of inlet guide vanes was designed to increase the relative entrance Mach number at the rotor hub section. The compressor with these inlet guide vanes was investigated over a range of equivalent tip speeds from 996 to 1801 feet per second. In addition to the over-all performance measurements, radial surveys of total pressure, static pressure, and air-flow angle were made upstream and downstream of the supersonic-compressor rotor. This report presents an analysis of the experimental results obtained.

APPARATUS

The compressor rotor and variable-component test rig used in this investigation were the same as those described in reference 1. The inlet guide vanes were installed so that the trailing edges of the inlet guide vanes at the pitch section were $1\frac{1}{4}$ inches upstream of the leading edge of the compressor rotor (fig. 1).

Inlet guide vanes. - The inlet guide vanes were designed to give 7° turning at the rotor hub (against rotation) and 0° turning at the rotor tip section. The purpose of this design turning was to increase the relative entrance Mach number at the compressor hub. The design of these guide vanes was based on the results published in reference 3, on the assumption that turning does not change with blade thickness. The 23 blades, which have a design solidity of 0.88, were 0.060-inch-thick sheet-metal plates shaped to the mean line of the 65-series airfoil. The leading and trailing edges were rounded to a radius of 0.030 inch.

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Instrumentation. - The instrumentation used in this investigation was essentially the same as that described in reference 1. The air weight flow through the compressor was measured by a 20-inch-diameter adjustable orifice. Compressor entrance conditions were measured in the depression tank. Over-all performance was evaluated from the rake measurements of total pressure and total temperature $13\frac{1}{2}$ inches downstream of the compressor rotor. A discharge survey station for measuring total pressure, static pressure, and air-flow angle was located $1\frac{1}{2}$ inches downstream of the compressor rotor. In addition, a survey instrument of the same type as that used downstream of the compressor rotor was located 3/4 inch upstream of the rotor. This survey instrument was located in the center of a passage between two inlet guide vanes.

PROCEDURE

Guide-vane calibration. - Complete surveys of total and static pressures and air-flow angles were obtained downstream of the inlet guide vanes before the compressor rotor was installed. The measured turning angle over the blade span is shown in figure 2. These data represent the average data taken over a range of entrance Mach numbers from 0.30 to 0.47. The maximum circumferential variation in turning angle appears to be about $\pm 3/4^{\circ}$ at the pitch section. Although the instrumentation was not fine enough for wake evaluations, total-pressure losses of about 7 percent of the entrance total pressure were found in the inlet-guide-vane wakes; whereas no measurable circumferential variation in static pressure was observed. Because these circumferential variations are quite small, the one survey taken near the center of a passage between two inlet guide vanes closely approximates the compressor inlet conditions.

Compressor investigations. - The compressor was operated over a range of equivalent tip speeds from 996 to 1801 feet per second. The data were obtained and the compressor performance was calculated in the same manner as given in reference 2.

RESULTS

Over-All Performance

The performance map in figure 3 was obtained with the 24-inch supersonic compressor rotor and the inlet guide vanes described. At an equivalent tip speed of 1604 feet per second, a maximum pressure ratio of 1.85 was obtained with an equivalent weight flow of about 59.7 pounds per second and an adiabatic efficiency of 0.76. At the overspeed condition of 1801 feet per second, a maximum pressure ratio of 2.02 was obtained at an equivalent weight flow of 66.5 pounds per second and an adiabatic efficiency of about 0.67. The maximum efficiency of 0.82 was obtained between the equivalent tip speeds of 1200 and 1400 feet per second. 1314

Figure 4 shows a corresponding performance map, reproduced from reference 2, for the compressor without inlet guide vanes. In general, over most of the range of this investigation, the mass flow was increased slightly, whereas the peak pressure ratio was decreased and the peak-efficiency range was moved toward the higher speed range through the use of the inlet guide vanes.

The performance parameters at peak pressure ratio for the compressor with and without inlet guide vanes are compared over the speed range in figure 5. The peak pressure ratio obtained is higher for the compressor without inlet guide vanes over the speed range investigated (fig. 5(a)). When the inlet guide vanes were installed, the peak pressure ratio at 1600 feet per second dropped from 1.93 to 1.85. The adiabatic efficiencies at maximum pressure ratio over the range of speeds tested are compared in figure 5(b). The use of inlet guide vanes resulted in a shifting of the maximum-efficiency region toward the higher speed range. The efficiency was found to fall off at a much greater rate with the inlet guide vanes as the speed is increased. At 1600 feet per second, the use of inlet guide vanes dropped the efficiency from 0.79 to 0.77. Figure 5(c) shows that the equivalent weight flow for the compressor with inlet guide vanes is higher over the entire speed range; at 1600 feet per second, the equivalent weight flow increased from 58.0 to 59.7 pounds per second.

Entrance Conditions

The axial-entrance Mach number for this compressor rotor with and without inlet guide vanes for an equivalent tip speed of 1600 feet per second is shown in figure 6(a). The higher axial-entrance Mach number over the entire passage with the inlet guide vanes corresponds to the increase in equivalent weight flow. This increase in axial-entrance Mach number resulting from the use of inlet guide vanes is reflected as an increase in the relative entrance Mach number over the entire blade passage (fig. 6(b)). The difference in the distribution of relative entrance Mach number over the rotor passage is partly a result of the fact that an absolute air angle of about 4° was measured at the compressor entrance without inlet guide vanes; whereas with inlet guide vanes the absolute air angle was very nearly zero at the compressor tip. There is, of course, a greater increase in relative entrance Mach number near the hub due to the turning in the inlet guide vanes. The relative entrance air angle (measured from the axial direction) as obtained from the survey instrument for this compressor with and without inlet guide vanes along with a plot of the entrance blade angle is shown in figure 6(c). There is little change in relative entrance-air angle for the compressor with and without inlet guide vanes.

Discharge Conditions

Axial-discharge Mach numbers over the discharge passage are compared in figure 7(a). With inlet guide vanes, the axial-discharge Mach number falls off at the tip considerably more than without inlet guide vanes. The radial profiles of the total-pressure ratio for the two configurations are shown in figure 7(b). Both curves peak near the center of the passage; the compressor without inlet guide vanes peaks at about 1.96 compared with 1.93 for the compressor with inlet guide vanes. With inlet guide vanes, there is a slight increase in total-pressure ratio near the compressor hub section.

Relative conditions at the discharge of the rotor can be obtained from the survey data taken behind the compressor rotor. The relative discharge Mach number over the blade span is shown in figure 8(a). Over a large portion of the blade span the relative discharge Mach number is higher with inlet guide vanes, whereas near the blade tips the curves become essentially the same. The passage recovery for the two configurations is shown in figure 8(b). As expected from the loss in efficiency with inlet guide vanes, the passage recovery is somewhat lower over most of the blade span. The difference between the two curves increases somewhat near the blade tips.

DISCUSSION

Mass flow. - It has been theorized (reference 4) that the maximum weight flow for this type of compressor would be obtained when the air enters parallel to the rear side of the blades. Measured relative entrance angles show that the air does not enter parallel to the rear side of the blades with either configuration. The average deviation of the measured relative entrance angle from the theorized maximum-mass-flow angle, however, is about the same in both cases. Because the relative entrance-air angle remains essentially the same and the relative entrance Mach number is increased (owing to the increased tangential component induced by the inlet guide vanes), the axial-entrance Mach number must be increased by the use of inlet guide vanes (figs. 5(c) and 6(a)). This condition accounted for the increased mass flow with inlet guide vanes.

<u>Pressure ratio and efficiency.</u> - The use of inlet guide vanes resulted in an increase in relative entrance Mach number. The compressor operating at this higher relative energy level should produce a higher total-pressure ratio; however, the compressor was unable to obtain this higher pressure (figs. 5 and 7(b)). This shortcoming of the compressor is an immediate result of an increase in the relative discharge Mach number (fig. 8(a)). This higher relative discharge Mach number with inlet guide vanes is obtained because the increased boundary layer and flow separation reduced the effective diffusion in the rotor passage. There is a considerable increase in this separation at the outer shroud, as shown by a comparison of the axial-discharge Mach number (fig. 7(a)), which indicates that there must have been a large transfer of the mass flow toward the compressor hub. Larger mixing losses therefore resulted from the use of guide vanes. Although higher Mach numbers were obtained at the compressor inlet through the use of guide vanes, the potential improvement in pressure ratio was more than offset by the increased flow separation in the rotor caused by the guide vanes. These mixing losses also adversely affect the efficiency. 1314

Two factors may contribute toward the increase in the severity of flow separation. Because the guide vanes caused higher relative Mach numbers near the rotor tip, higher adverse pressure gradients through the shock and, hence, increased separation near the tip might be expected. Another factor contributing to the unfavorable results obtained with the guide vanes involves the effect of the guide-vane wakes in creating an unsteady flow field at the rotor inlet. In the unsteady field created by the inlet guide vanes, the normal shock tends to oscillate in the rotor passage. If at any time the shock is moved sufficiently forward to be expelled, the compressor will stall. Therefore, the greater the amplitude of the oscillation, the farther downstream must be the effective position of the normal shock. In this manner, because it is impossible to stablize the normal shock as near the minimum section as is possible in a steady flow field, the addition of inlet guide vanes results in a decrease in compressor pressure ratio and efficiency. It appears that this effect of guide-vane wakes is an inherent loss encountered when inlet guide vanes are used with this type of compressor. If the inlet guide vanes are to increase the pressure ratio, the guide vanes must have sufficient turning to overcome this inherent loss.

SUMMARY OF RESULTS

The following results were obtained from a comparison of the performance of the 24-inch axial-flow supersonic-compressor rotor with and without inlet guide vanes:

1. In general, the use of these inlet guide vanes resulted in a decrease in maximum pressure ratio and adiabatic efficiency and a slight increase in equivalent mass flow.

2. An increase in the severity of flow separation in the compressor resulted in poorer diffusion behind the normal shock when inlet guide vanes were used.

3. It is indicated that the unsteady field at the rotor entrance resulting from the guide-vane wakes results in an inherent loss when inlet guide vanes are used with this type of compressor. If inlet guide vanes are to be effective in improving the performance of the compressor, these losses must be considered in the design of the inlet guide vanes.

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3. Zimney, Charles M., and Lappi, Viola M.: Data for Design of Entrance Vanes from Two-Dimensional Tests of Airfoils in Cascade. NACA ACR L5G18, 1945.

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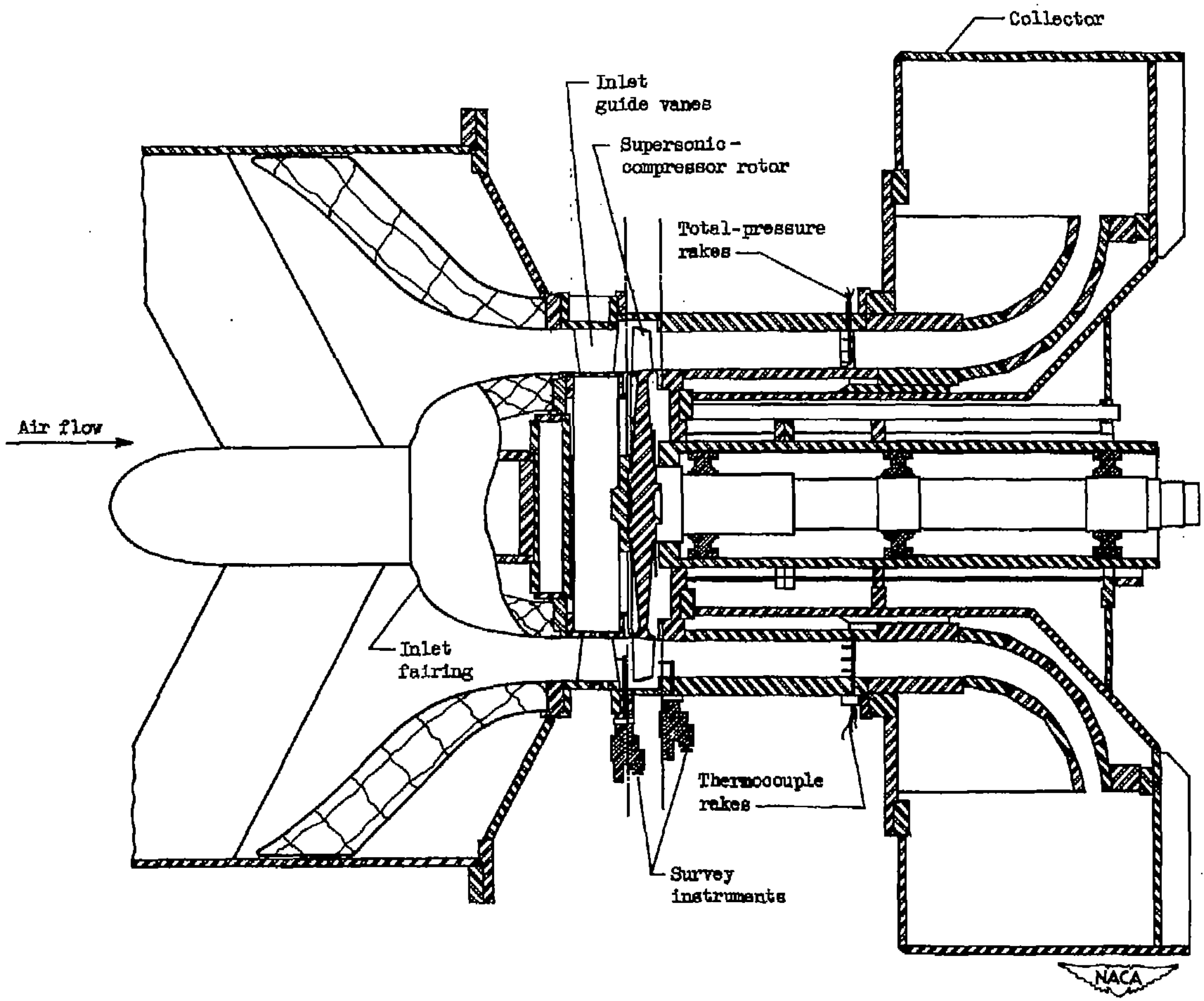

Figure 1. - Sectional view of variable-component supersonic-compressor installation with inlet guide vanes.

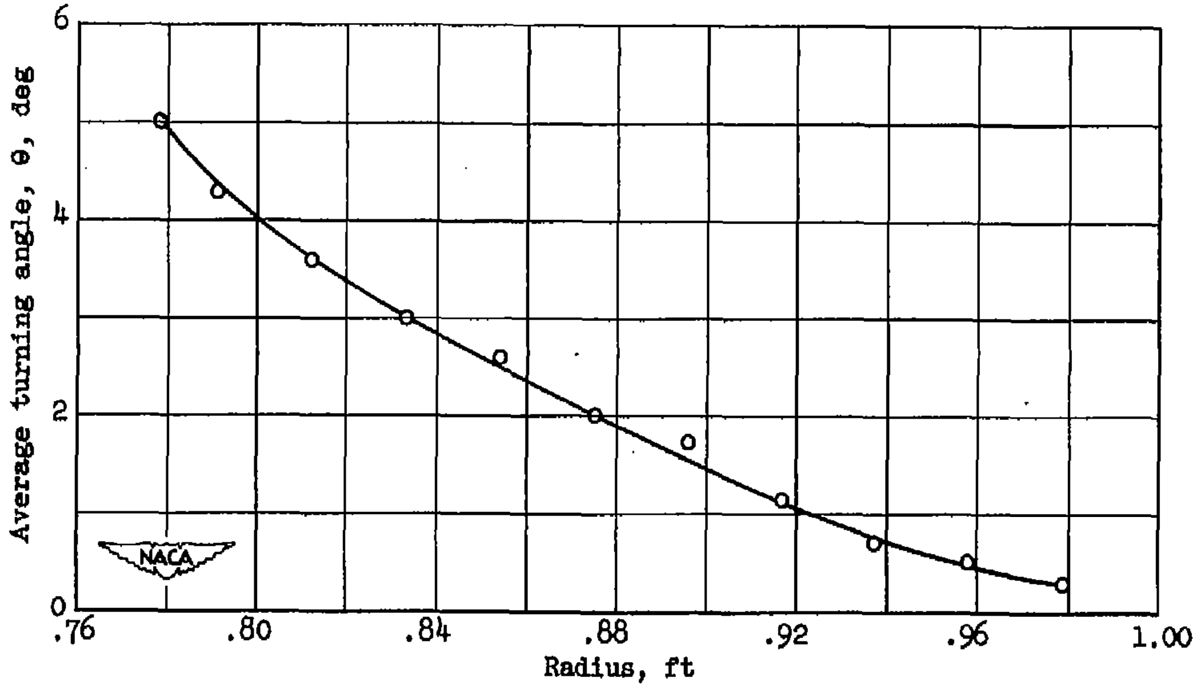

Figure 2. - Average experimental turning angle of inlet guide vanes.

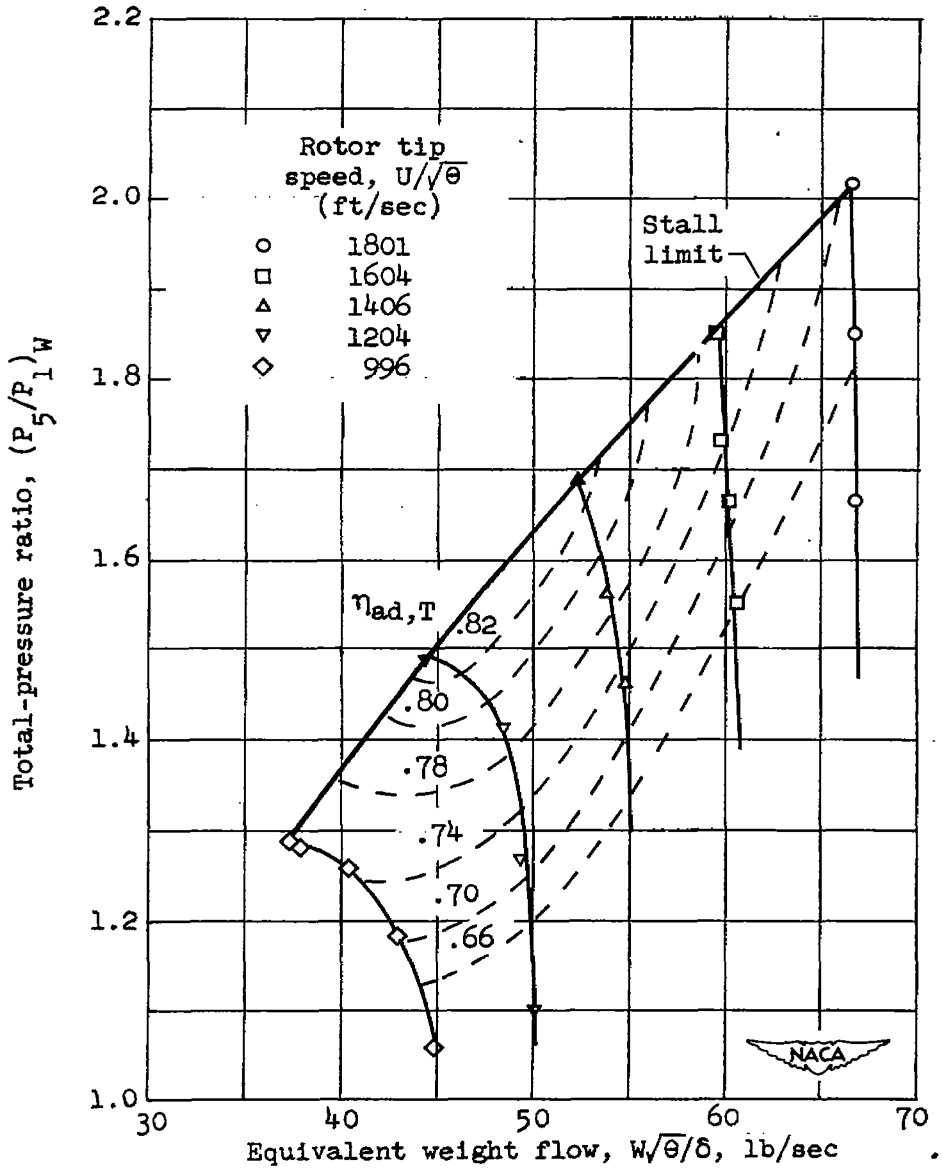

Figure 3. - Performance characteristics of 24-inch supersonic-compressor rotor with inlet guide vanes.

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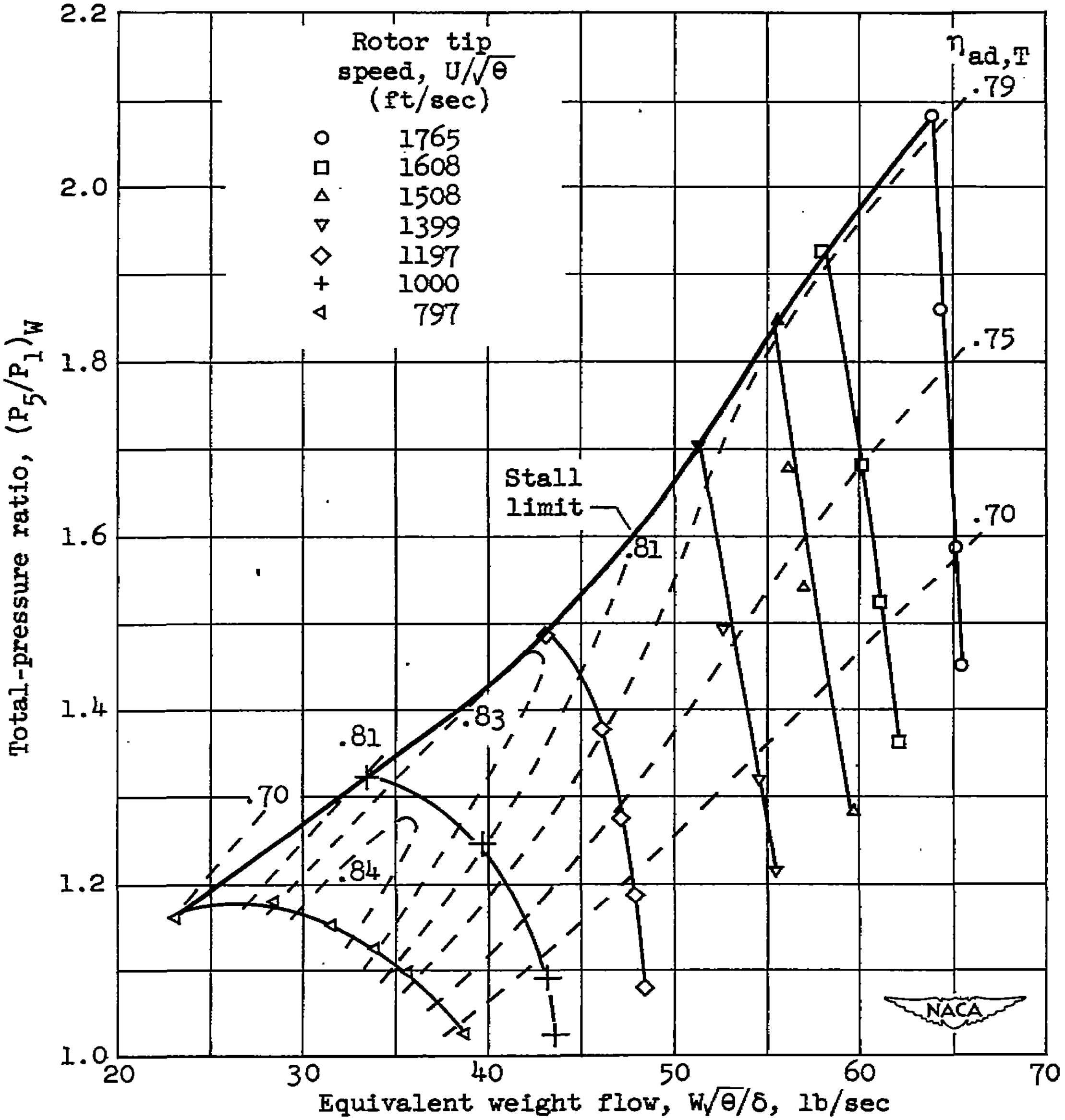

Figure 4. - Performance characteristics of 24-inch supersonic-compressor rotor without inlet guide vanes (fig. 2, reference 2).

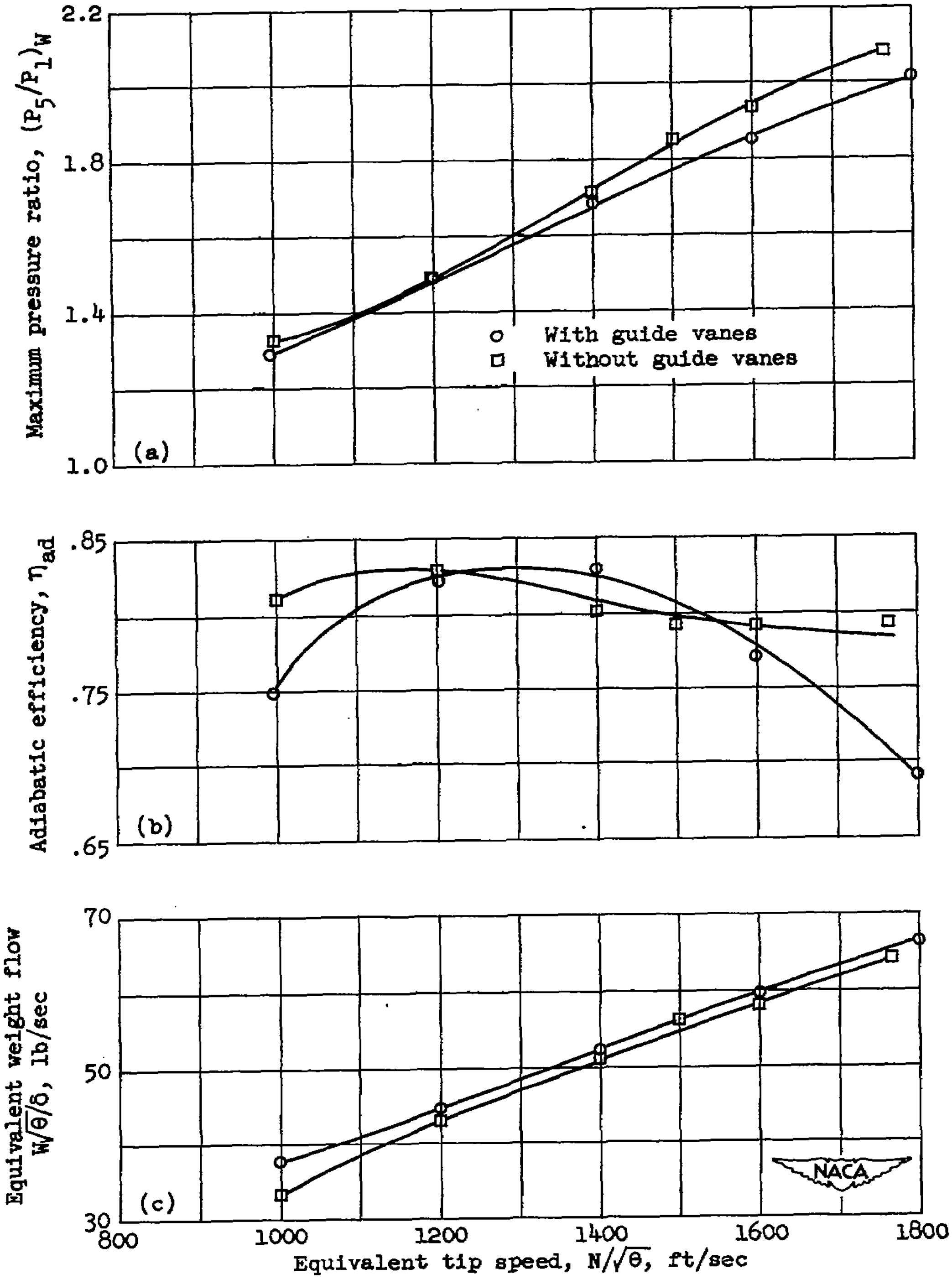

Figure 5. - Performance of 24-inch supersonic-compressor rotor with and without inlet guide vanes at maximum-pressure-ratio conditions.

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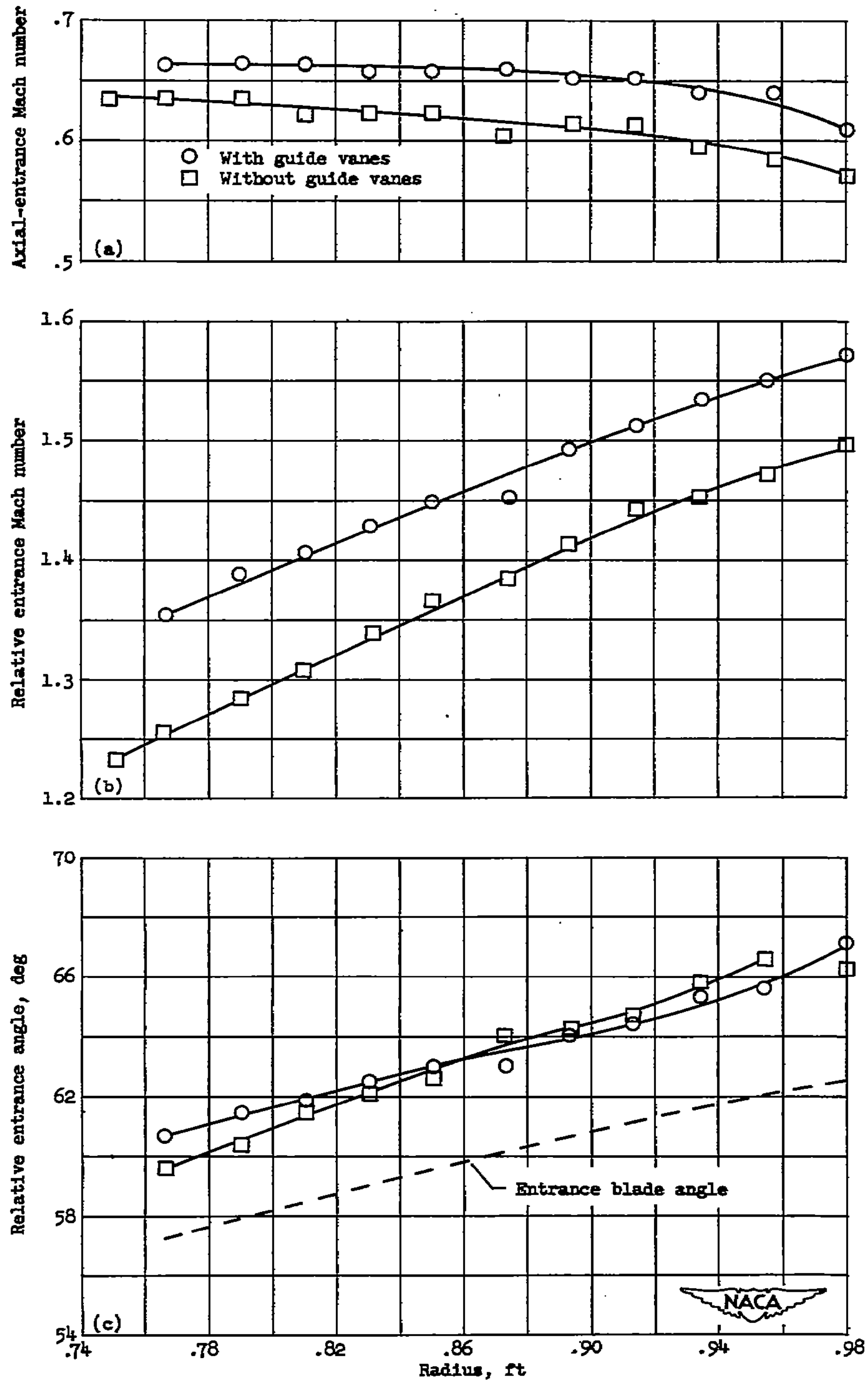

Figure 6. - Entrance conditions for supersonic compressor with and without inlet guide vanes as measured by survey instrument between inlet guide vanes and rotor. Equivalent tip speed, 1600 feet per second.

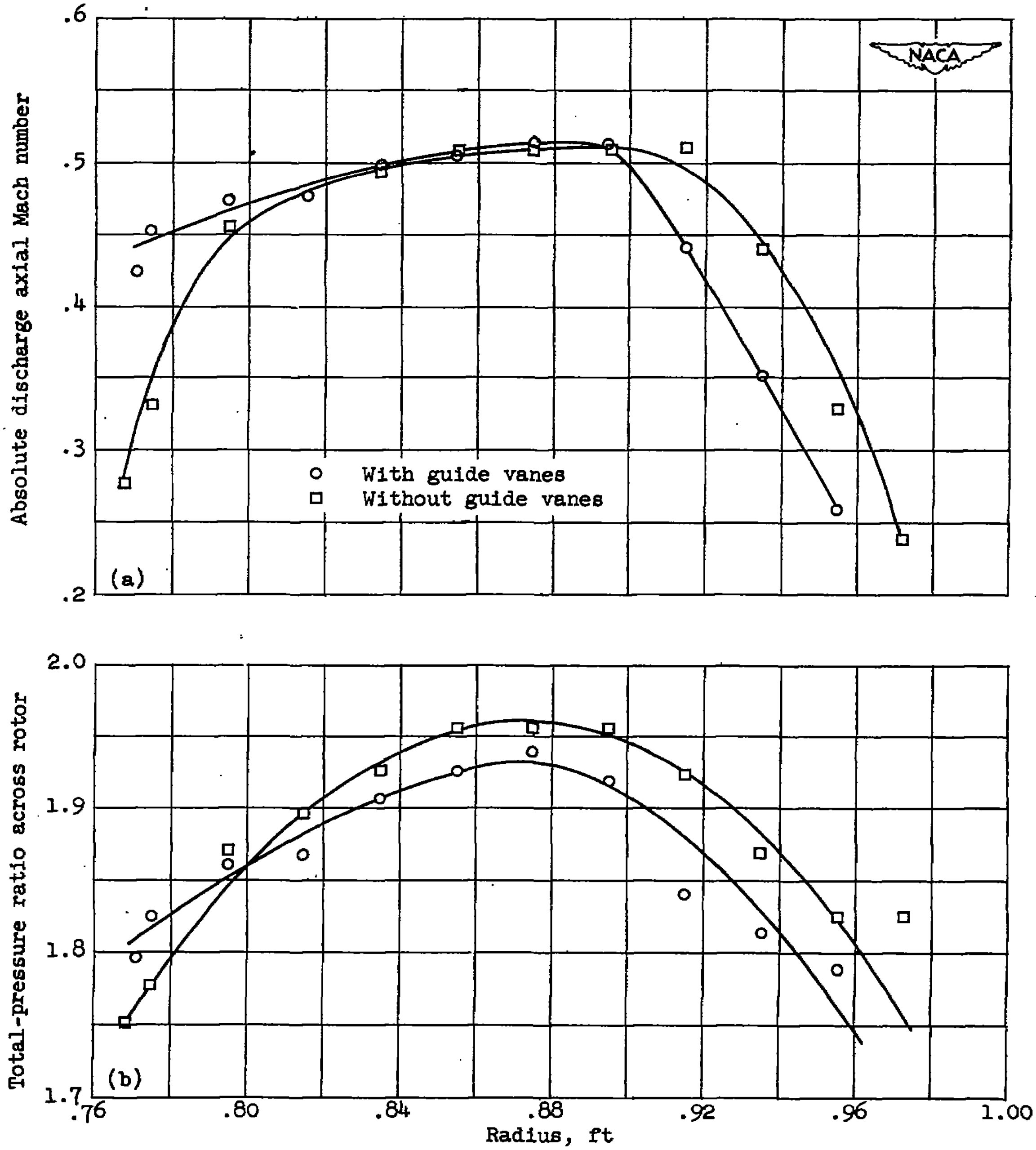

Figure 7. - Absolute discharge profiles of 24-inch supersonic-compressor rotor with and without inlet guide vanes at maximum-pressure-ratio conditions. Equivalent tip speed, approximately 1600 feet per second.

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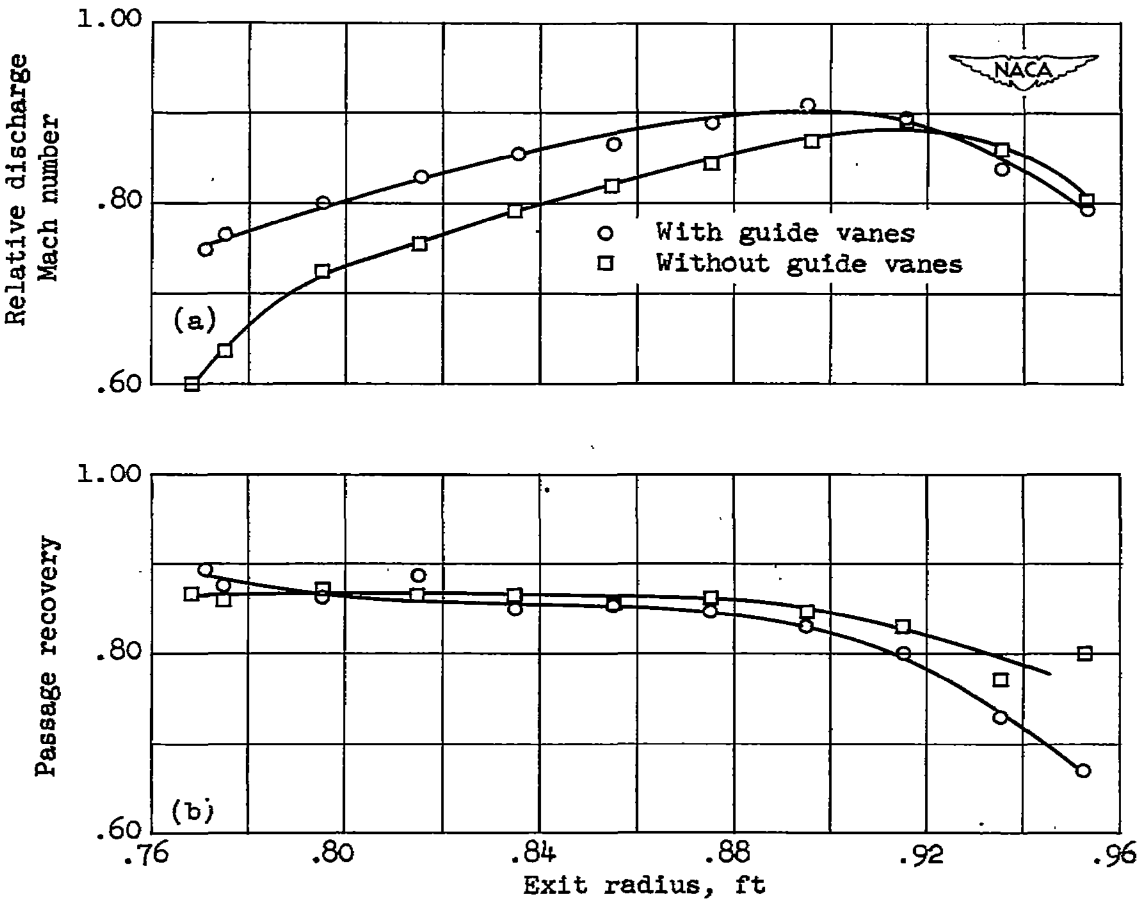

Figure 8. - Relative discharge profiles of 24-inch supersonic-compressor rotor with and without inlet guide vanes at maximum-pressure-ratio conditions. Equivalent tip speed, approximately 1600 feet per second.

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